Explaining Dark Matter and Dark Energy from Bose-Einstein condensate

Λ ?

What do we know about DM and DE?

- Constituents of our universe
- Observations
- The origin of DM and DE – what is the cosmological constant?

→ One possible explanation: DM formed a BEC at very early epochs!

→ Scalar field dark matter theory ~ QG

Message:

Condensate of bosons of mass less than 1 eV via a quantum potential gives rise to a cosmological constant

Saurya Das and Rajat K Bhaduri 2015 *Class. Quantum Grav.* **32** 105003

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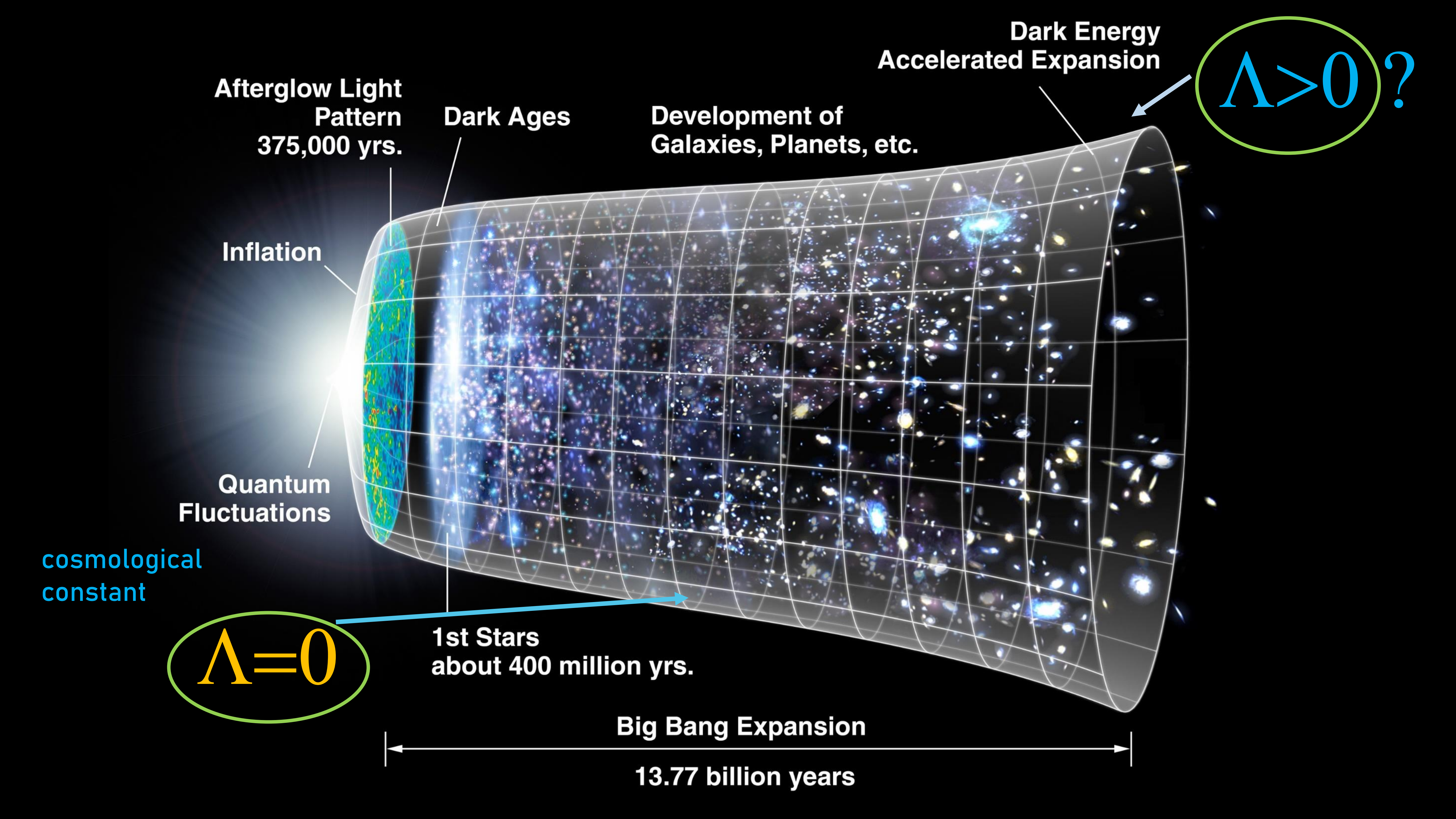
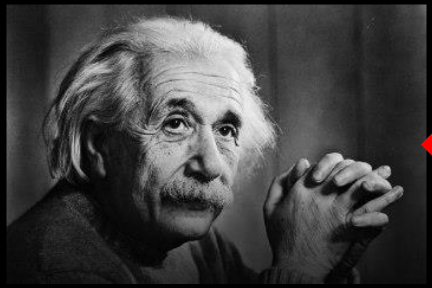
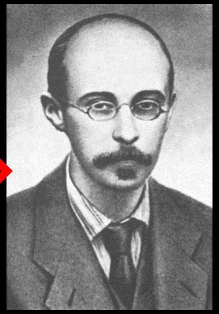


Dark Energy
Accelerated Expansion
Λ>0?
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
cosmological
constant
Λ=0
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years

What is the origin of the cosmological constant?



static



dynamical

original Einstein's Equation

$$\underbrace{R_{\mu\nu} - \tfrac{1}{2}Rg_{\mu\nu}}_{} = (8\pi G)T_{\mu\nu}$$

curvature of spacetime

constants

energy and momentum

Finite universe in space!

Matter/energy content

corrected Einstein Equation

$$R_{\mu\nu} - \frac{1}{2}R\, g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

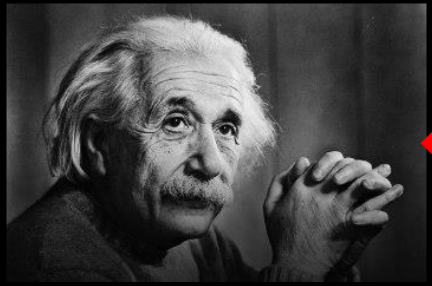
<0

compensate the expansion

This form could have allowed for non-static solution ↔ Einstein believed in a temporally infinite universe!

expanding universe

What is the origin of the cosmological constant?



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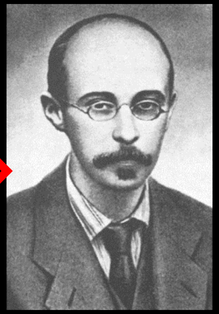

dynamical

original Einstein's Equation

$$\underbrace{R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu}}_{\text{curvature of spacetime}} = (8\pi G)T_{\mu\nu}$$

curvature of spacetime

constants

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Matter/energy content

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corrected Einstein Equation

$$R_{\mu\nu} - \frac{1}{2}R\,g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

$\Lambda < 0$

compensate the expansion

But is this really a stable fix?

What is the origin of the cosmological constant?

dynamical

Friedmann: the cosmological constant term is an unstable mathematical fix

↓

The theory with Λ describes an unstable universe!

↓

Einstein: Λ should be zero!

↓

Dynamical universe!

Experiments prove that the universe is in fact expanding

Hubble: Linear relation between redshift velocity and distance (brightness)

What is the origin of the cosmological constant?

dynamical

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Dynamical universe!

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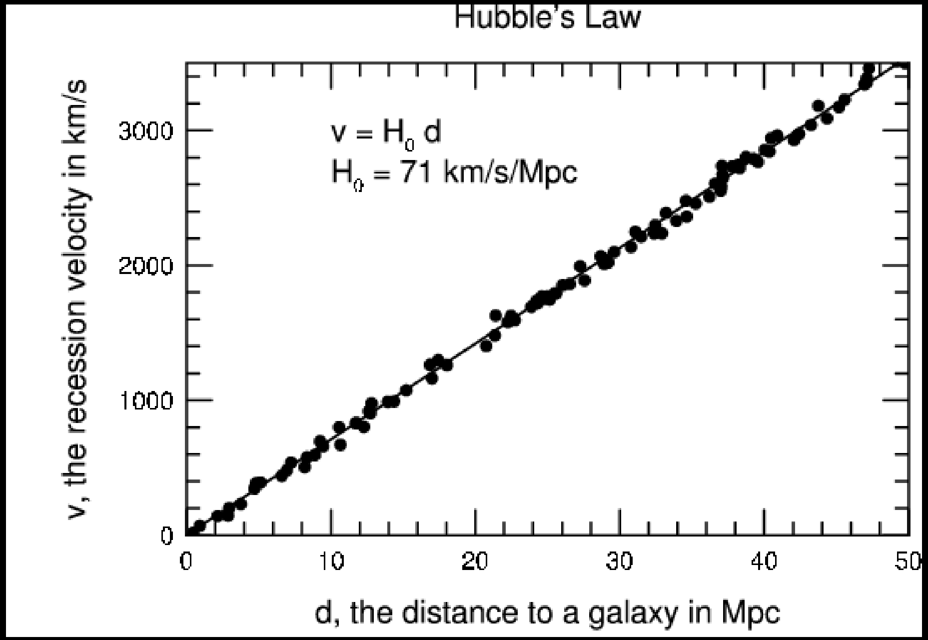


Dynamical universe: crucial observations and consequences

Backwards extrapolated universe model

$\Lambda=0$

uniform expansion

At the beginning: different material structure (plasma)

Big Bang theory

Phase transition driven exponential expansion!

Describes the inflation epoch

Experimental proof: cosmic microwave background radiation

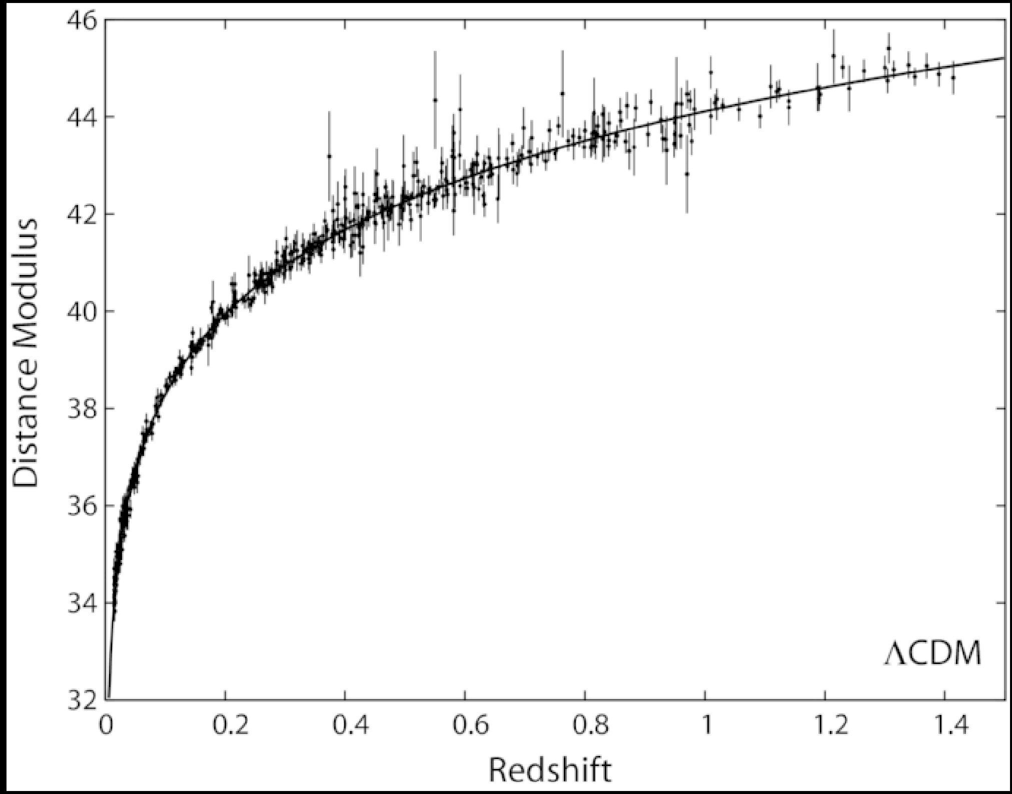
Dynamical universe: crucial observations and consequences

Λ=0 uniform expansion

1998

Type Ia supernovae measurements (precise – error reduction)

redshift velocity vs luminosity



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Dynamical universe: crucial observations and consequences

$\Lambda \neq 0$?

Dark energy

accelerated expansion! (Λ>0)

$\Lambda > 0$!

Friedmann: equation for the scale factor (a)

For homogeneous and isotropic universe: $-c^2 \mathrm{d}\tau^2 = -c^2 \mathrm{d}t^2 + a(t)^2 \mathrm{d}\boldsymbol{\Sigma}^2$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3}$$

energy density

pressure

accelerate

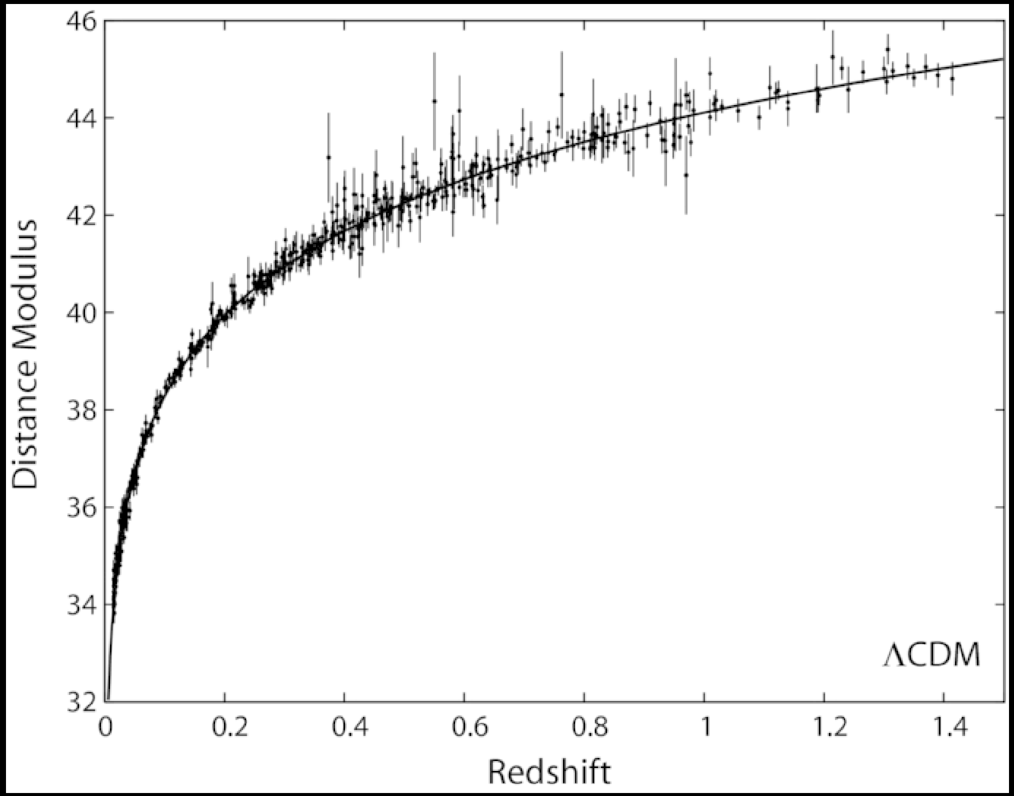
decelerate

scale factor: a(t)

1998

Type Ia supernovae measurements (precise – error reduction)

redshift velocity vs luminosity



Dynamical universe: crucial observations and consequences

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Friedmann:

ΛCDM model

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scale factor: a(t)

decelerate

- Λ is tiny
- the dominating matter component is cold

The constituents of our universe

<u>in recent epochs:</u>

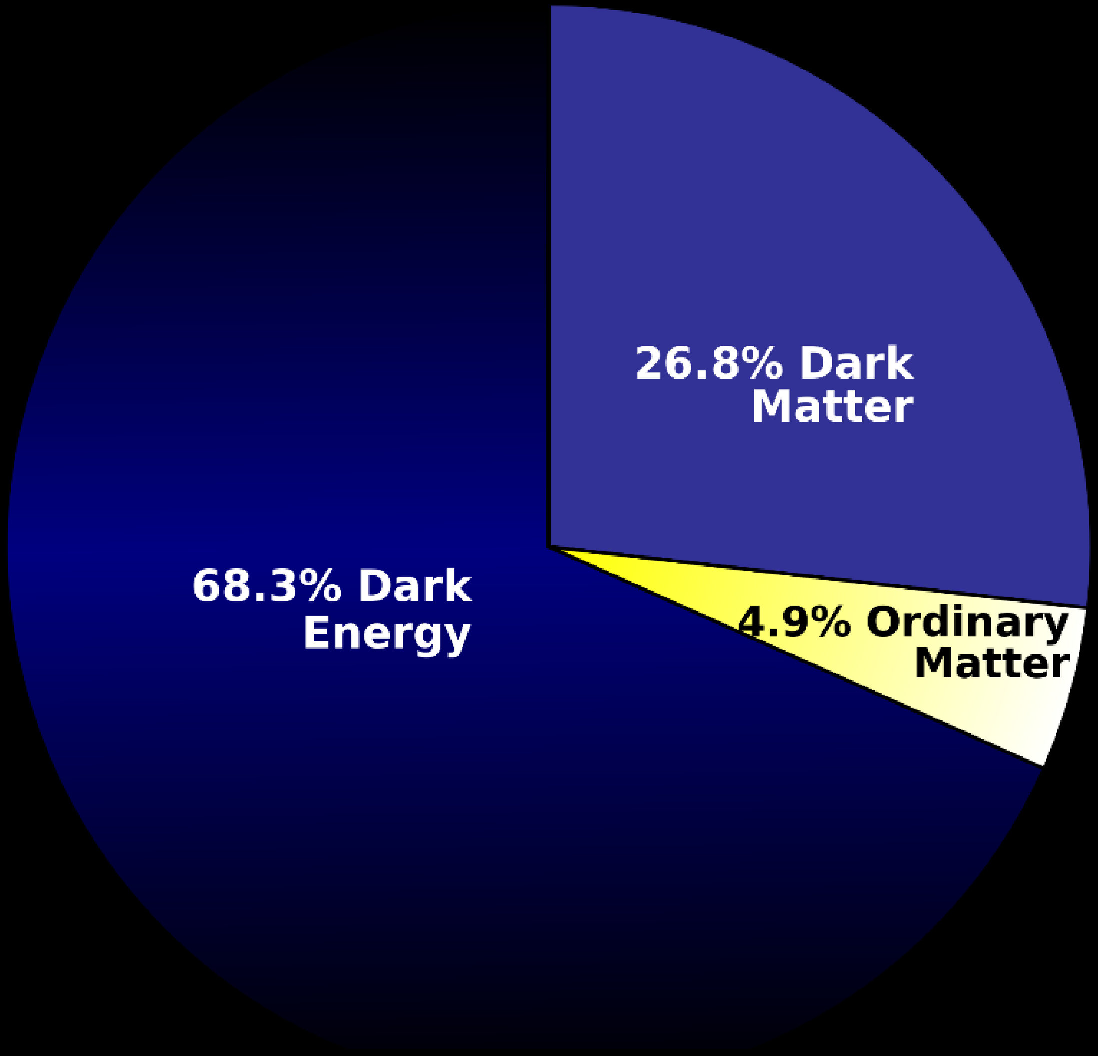
- Dark energy is dominating: accelerated expansion

+

- many gravitational effects cannot be explained with the amount of ordinary matter:
    - CMB, gravitatinal lensing, rotating galaxies

|

there must be a great fraction of unknown Dark matter



no interaction with EM radiation, non-baryonic

A possible Dark Matter model

from criteria for dominating quantum-effects

Cold Dark Matter (CDM): small momentum, zero pressure

Start with an ideal gas of bosons: *massive* — form a BEC under T_c

T_c = ?

for ultrarelativistic, noninteracting bosons

$$T_c = \frac{6 \times 10^{-12} \, \mathrm{kg}^{1/3}}{m^{1/3} \; a} K$$

$$T_c = \frac{\hbar c}{k_B} \left(\frac{N \pi^2}{V \eta \zeta(3)} \right)^{1/3}$$

V equals to Hubble radius cubed: L_0^3

average interparticle distance is smaller than the de Broglie wavelength

For m small enough T_c is high enough for the BEC to form at early epochs!

m=?

A possible Dark Matter model

Cold Dark Matter (CDM): small momentum, zero pressure

EOM – gravitational interaction

Quantum description – quantum corrected Friedmann equation

BEC – macroscopic wavefunction $\phi = \mathcal{R}e^{iS} \quad (\mathcal{R}(x^a), S(x^a))$

we basically connect the metric with it

Trick: Bohmian (quantum) trajectories defined by a velocity field from the paramters of the wavefunction

$$u_a = \hbar \; \partial_a S/m$$

induced metric:

$$h_{ab} = g_{ab} - u_a u_b$$

A possible Dark Matter model

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Quantum description – quantum corrected Friedmann equation

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$$u_a = \hbar \; \partial_a S/m$$

$$h_{ab} = g_{ab} - u_a u_b$$

Derive the quantum corrected Friedmann equation with this metric

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\hbar^2}{3m^2} h^{ab}\left(\frac{\Box\mathcal{R}}{\mathcal{R}}\right)_{;a;b}$$

DM!

$\sim\Lambda_q$

Dark energy

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$\sim \Lambda_q$

$$\Lambda_Q = \frac{\hbar^2}{m^2 c^2} h^{ab} \left(\frac{\Box \mathcal{R}}{\mathcal{R}} \right)_{;a;b}$$

from the wavefunction ϕ

Requirements from the amplitude R:

- **nonzero**
- **spread out uniformly over L_0 (Hubble radius)** – cosmological principle

$$\mathcal{R} = \mathcal{R}_0 \exp(-r^2/L_0^2)$$

harmonic oscillator ground state

L_0 now: characteristic range of the wavefunction
→Bosons → Klein Gordon → Compton wavelength

A possible Dark Matter model

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$L_0 = 1.4\times10^{26}\ metre$

$$\Lambda_Q = \frac{1}{L_0^2} = \left(\frac{mc}{h}\right)^2$$

m= 10^{-32} eV

$$\Lambda_Q = 10^{-52}\ (metre)^{-2}$$

A possible Dark Matter model

Cold Dark Matter (CDM): small momentum, zero pressure

Quantum description – quantum corrected Friedmann equation

$L_0 = 1.4 \times 10^{26}\, metre$

$$\Lambda_Q = \frac{1}{L_0^2} = \left(\frac{mc}{h}\right)^2$$

m= 10^{-32} eV = 10^{-68} kg

$$\Lambda_Q = 10^{-52}\,(metre)^{-2}$$

$$T_c = \frac{6 \times 10^{-12}\, kg^{1/3}}{m^{1/3}\, a} K$$

$T_c = 10^{11}\, a^{-1}$ K

very high – early stages

extremely tiny : 37 order of magnitude less than the electron!

BEC of tiny mass bosons formed at early epochs of the unvierse

A possible Dark Matter model

Cold Dark Matter (CDM): small momentum, zero pressure

Viable candidates for these bosons:

gravitons

- Derivation from GR is not good → they are massless…

- Nonlinear completion of the Fierz-Pauli action → mass!
- Spontaneous symmetry breaking → mass!
- …

$m \sim 10^{-32}$ eV

axions

- Too hypothetical
- Requires to expand SM of particle physics

Summary: A possible Dark Matter model

Cold Dark Matter (CDM): small momentum, zero pressure

BEC as CDM → gives rise to Dark Energy through the cosmological constant

$$T_c = \frac{6 \times 10^{-12}}{m^{1/3}\ a} K$$

m= 10^{-32} eV

$$\Lambda_Q = 10^{-52}\ (metre)^{-2}$$

$T_c = 10^{11}\ a^{-1}$ K ← very high – early stages

BEC of tiny mass bosons formed at early epochs of the unvierse

Viable candidates for these bosons:

massive gravitons